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# Sedimentation Assessment and Mitigation Strategies for the Unda River, Bali, Indonesia

**I Putu Gustave Suryantara Pariartha[1*], I Gede Arta Wibawa[2], Luh Putu Puspawati[3], Mawiti Infantri Yekti[4]**
[1]Faculty of Engineering, Udayana University, Bali, Indonesia
[2]Faculty of Mathematics and Natural Science, Udayana University, Bali, Indonesia.
[3]Faculty of Cultural Science, Udayana University, Bali, Indonesia.
[4]Faculty of Engineering, Universitas Negeri Yogyakarta, Yogyakarta, Indonesia.
[*)]Email correspoding author: gustave_sp@unud.ac.id

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**Abstract**

*The Unda River Basin has experienced substantial degradation due to deforestation, land-use change, landslides, soil erosion, and sediment accumulation within the river and its check dams. Excessive erosion and sedimentation reduce the hydraulic capacity of the river and the effectiveness of sediment-control infrastructure. This study aimed to estimate the potential sediment volume in the Unda River Basin and formulate structural and non-structural mitigation measures. The Universal Soil Loss Equation (USLE) was applied to estimate watershed erosion and the associated sediment volume. The results indicate that most check dams in the basin are heavily filled with sediment. The estimated annual sediment volume is approximately 118,115.70 m³, which may be used as the target volume for annual dredging. Under a five-year maintenance interval, approximately 249,554.37 m³ and 341,024.12 m³ of sediment should be removed from the two uppermost check dams, respectively. Under a ten-year interval, the required dredging volumes from the three uppermost check dams are approximately 249,554.37 m³, 378,787.88 m³, and 552,814.72 m³, respectively. Structural mitigation should therefore prioritize the initial removal of accumulated sediment followed by scheduled dredging to restore and maintain check-dam capacity. Non-structural measures should include regulatory oversight, sediment-removal monitoring, community participation, and village-level management. The findings provide a basis for establishing an integrated and adaptive sediment-management strategy for the Unda River Basin.*

**Keywords:** *Watershed degradation, soil erosion, sediment yield assessment, diasater mitigation*

**Abstrak**

*Daerah Aliran Sungai Tukad Unda telah mengalami degradasi akibat berbagai permasalahan pengelolaan, seperti deforestasi, penumpukan sedimen di sungai, longsor, erosi tanah, serta perubahan tata guna lahan yang berkontribusi pada meluasnya wilayah terdegradasi. Tingginya laju erosi dan sedimentasi dapat mengurangi kemampuan sungai dalam mengalirkan air. Tujuan dari penelitian ini adalah melakukan analisa volume sedimentasi dan memberikan rekomendasi mitigasi baik secara struktural maupun non-struktural di DAS Unda. Penelitian ini menggunakan metode Universal Soil Loss Equation untuk memprediksi volume sedimentasi dengan menghitung laju erosi di DAS. Hasil penelitian menunjukkan bahwa sebagian besar check dam di sepanjang DAS Unda telah mengalami sedimentasi yang cukup parah. Sebagai upaya mitigasi, pengerukan sedimen pada bangunan ini dapat dilakukan setiap tahun dengan volume total sekitar 118.115,70 m³. Namun, jika dilakukan lima tahunan, diperlukan penggalian 249.554,37 m³ sedimen pada check dam paling hulu dalam sistem, kemudian diikuti dengan penambangan sekitar 341.024,12 m³ sedimen pada check dam di bagian hilir berikutnya. Apabila dipilih opsi pengerukan sepuluh tahunan, maka perlu dilakukan penggalian berturut-turut sebesar 249.554,37 m³, 378.787,88 m³, dan 552.814,72 m³ dari tiga check dam utama di bagian hulu. Proses pengerukan ini dapat dikelola oleh pemerintah atau melibatkan partisipasi masyarakat melalui pengelolaan di tingkat desa.*

**Kata kunci:** *Degradasi daerah aliran sungai, erosi tanah, analisis hasil sedimen, mitigasi bencana*

## Introduction

The Unda River is an inter-regency river system in eastern Bali, Indonesia, with a watershed area of approximately 223.07 km². The basin comprises 200.46 km² in Karangasem Regency, 11.43 km² in Klungkung Regency, and 11.18 km² in Bangli Regency. Originating near Mount Agung in Karangasem, the river flows southward before discharging into the sea at Gunaksa Beach in Klungkung Regency (Sutapa, 2010). Over time, the watershed has experienced substantial environmental degradation associated with deforestation, land-use change, landslides, soil erosion, and sediment accumulation within the river channel. Consequently, the Unda River Basin has been classified as a critical watershed and designated as a priority area for integrated water-resources management. Hydrological records from 2013–2016 indicate considerable flow variability, with recorded discharges ranging from a minimum of 0.17 m³/s to a maximum of 53.4 m³/s (Toban et al., 2016).

Soil erosion and sedimentation are closely interconnected watershed processes that can significantly affect river morphology and hydraulic performance. Material eroded from hillslopes is transported through the drainage network and may subsequently accumulate within river channels and hydraulic structures. Excessive deposition raises the riverbed and reduces the effective cross-sectional area available for flow, thereby decreasing the river's conveyance capacity (Mahmood et al., 2022; Ramsof et al., 2025). During the rainy season, this loss of capacity can produce higher water levels and increase the likelihood of overbank flooding, even when the magnitude of river discharge remains unchanged (Chang and Ab. Ghani, 2024). Sediment deposited during low-flow periods may therefore contribute to greater flood hazards during subsequent high-flow events.

In addition to affecting river conveyance, sediment accumulation can impair the performance and shorten the service life of check dams. These structures are designed to intercept sediment, stabilize riverbeds, and reduce downstream sediment transport. However, progressive sediment deposition occupies the available storage space and gradually reduces their trapping capacity (Feng et al., 2021; Yekti et al., 2024). Once the storage capacity has been substantially depleted, a check dam becomes less effective in controlling sediment movement and attenuating sediment-related hazards. This problem has become increasingly apparent along the Unda River, where several check dams have accumulated considerable volumes of sediment. Without appropriate maintenance and sediment removal, the functional capacity of these structures is expected to continue declining (Kardhana et al., 2024).

Sedimentation in the Unda River is particularly important because its downstream area has been designated as a strategic development zone for the Bali Cultural Centre. This area is situated within the former mining zone of Klungkung Regency, covering parts of Klungkung and Dawan districts and commonly referred to as the Gunaksa area. Located near the river mouth and the coastline, the area is characterized predominantly by flat to gently sloping terrain. Its position at the downstream end of the watershed makes it a natural receiving zone for sediment transported from upstream areas. The combination of intensive upstream erosion, reduced check-dam capacity, and planned downstream development highlights the need for a systematic assessment of sediment sources and accumulation (Wiyanti et al., 2022) .

Given the environmental degradation of the watershed, the declining effectiveness of sediment-control structures, and the strategic importance of the downstream area, comprehensive sediment-management measures are urgently required (Lucas-Borja et al., 2021) . Such measures are necessary to minimize potential impacts on human safety, infrastructure, economic activities, and aquatic and terrestrial environments. Effective management should be supported by an assessment of potential soil erosion throughout the watershed, an evaluation of sediment accumulation within existing check dams, and the formulation of targeted structural and non-structural mitigation measures (Hidayati et al., 2021). Accordingly, this study aims to estimate potential erosion-derived sediment in the Unda River Basin, evaluate sediment accumulation in its check dams, and propose appropriate mitigation and maintenance strategies.

The potential supply of sediment from the watershed was evaluated using the Universal Soil Loss Equation (USLE). USLE is an empirical model developed to estimate long-term average annual soil loss resulting primarily from sheet, rill, and interrill erosion. The model incorporates the effects of rainfall erosivity, soil erodibility, slope length and steepness, land cover, and soil-conservation practices. It has been widely applied because of its relatively simple parameterization, flexible implementation, moderate data requirements, and extensive scientific documentation. USLE-based analysis can therefore provide valuable information for identifying erosion-prone areas and supporting soil- and water-conservation planning (Alewell et al., 2019; Borrelli

et al., 2021; Majhi et al., 2021). In this study, estimated soil loss is used to represent the potential sediment supply from the watershed. Where sediment volume is derived from soil-loss estimates, appropriate sediment-delivery and mass-to-volume conversion factors must be considered because not all eroded material is transported to or deposited within the river and its check dams. Current watershed management studies increasingly integrate erosion assessment, sediment management, and flood-risk reduction. The Universal Soil Loss Equation (USLE) is widely used to estimate long-term soil loss because of its simplicity, data accessibility, and suitability for spatial analysis.

Previous research on erosion and sedimentation has primarily focused on estimating soil loss and mapping erosion susceptibility, providing a foundation for identifying sediment sources and vulnerable areas. However, limited attention has been given to translating these estimates into sediment removal volumes, check dam maintenance schedules, and integrated mitigation strategies. This study addresses this gap in the Unda River Basin by linking estimated sediment accumulation with check dam storage capacity and evaluating annual excavation scenarios to inform maintenance planning. It further integrates structural measures, including dredging and controlled sediment mining, with non-structural measures involving government coordination, community participation, and disaster-risk awareness. The study's contribution lies in connecting erosion assessment with practical sediment management, providing a basis for planning sediment removal and coordinating mitigation at the basin scale.
The urgency of this research as continued sediment accumulation reduces river conveyance and check dam storage capacity, thereby increasing downstream flood and sedimentation risks. These risks are particularly significant in the Gunaksa area, where the Bali Cultural Centre is being developed near the Unda River estuary.

## Research Methods

### The rainfall analysis

The USLE analysis was organised as a sequential frameworks. Firstly, the rainfall data is checked for their consistency. Reliable rainfall data are essential for estimating rainfall erosivity and soil erosion using the Universal Soil Loss Equation (USLE). However, long-term rainfall records may contain inconsistencies caused by changes in measuring instruments, station relocation, environmental conditions, observation procedures, or data-recording practices. These inconsistencies may introduce bias and reduce the accuracy of hydrological and erosion analyses. Therefore, the consistency of the rainfall records must be evaluated before the data are used in the USLE analysis.

The method for consistency test is the RAPS (Rescaled Adjusted Partial Sums) method (Suliwa et al., 2024). The consistency test is performed on annual rainfall data to identify any deviations, allowing for the determination of whether the data is suitable for hydrological analysis. The consistency test uses data from the station itself by calculating the cumulative deviation from the mean, divided by the square root of the cumulative mean squared deviation from the average value. The formula for this calculation is provided below:

So* =0

$$Sk^* = \sum_{i=1}^{k}(\bar{y} - yi) \quad k = 1,2 \quad n \tag{1}$$

$$Sk^{**} = \frac{Sk^*}{Dy} \tag{2}$$

$$Dy^2 = \sum_{i=1}^{n} \frac{(yi-\bar{y})}{n} \tag{3}$$

$$Q = \max Sk^{**} \ , 0 \le k \le n, \text{ or} \tag{4}$$

$$R = \text{Max } Sk^{**} \ , \min Sk^{**} \quad 0 \le k \le n \tag{5}$$

Where Yi is the rainfall data i, Y is the average rainfall data i (mm), Dy is the standard deviation, n is the number of data. Next, the calculated Q and R statistics are compared with the corresponding critical values presented in Table 1.

**Table 1. Statistic al values of Q and R**

| N | $Q/\sqrt{N}$ | | | $R/\sqrt{N}$ | | |
|---|---|---|---|---|---|---|
| | **90%** | **95%** | **99%** | **90%** | **95%** | **99%** |
| 10 | 1.05 | 1.14 | 1.29 | 1.21 | 1.28 | 1.38 |
| 20 | 1.10 | 1.22 | 1.42 | 1.34 | 1.43 | 1.60 |
| 30 | 1.12 | 1.24 | 1.48 | 1.40 | 1.50 | 1.70 |
| 40 | 1.14 | 1.27 | 1.52 | 1.44 | 1.55 | 1.78 |
| 100 | 1.17 | 1.29 | 1.55 | 1.50 | 1.62 | 1.85 |
| | 1.22 | 1.36 | 1.63 | 1.62 | 1.75 | 2.00 |

Rainfall observations recorded at individual rain-gauge stations represent point rainfall and may not adequately reflect the spatial distribution of precipitation across an entire watershed. This is because point-based rainfall measurements generally represent only a limited surrounding area, typically less than 4 km² (Page et al., 2022). Rain gauge stations scattered throughout a watershed can be considered as points.

Point rainfall records that satisfied the consistency requirements were transformed into representative watershed-average rainfall using the Thiessen polygon method. This approach accounts for the spatial contribution of each rainfall station by

dividing the watershed into influence zones based on the relative proximity of the gauges. Thiessen polygons, which are closely associated with Voronoi diagrams and Delaunay triangulation, have long been applied in climatology and other disciplines to analyze spatial proximity and neighborhood relationships. Each rainfall station is assigned a weighting coefficient corresponding to the proportion of the watershed area represented by its polygon.

The areal rainfall is subsequently calculated as the weighted average of rainfall recorded at all stations. Originally introduced by Thiessen et al. (1911), this method is particularly suitable for watersheds with an uneven spatial distribution of rainfall stations (Kusumawardani et al., 2017; Page et al., 2022). The Thiessen polygon distribution used in this study is shown in Figure 1. The equation for calculating areal rainfall is presented in Equation (6).

$$\bar{p} = \frac{A_1P_1+A_2\,P_2+A_3P_3+\cdots\cdots\cdots\cdots A_nP_n}{A_1+A_2+A_3+\cdots\cdots\cdots\cdots A_n} \quad (6)$$

Where $\bar{P}$ is the average rainfall (mm), $P_1$, $P_2$ ...$P_n$ are the rainfall measurements recorded at stations1, 2,3...n (mm), and $A_1$,A….$A_n$ are the corresponding areas represented by each station (km²)

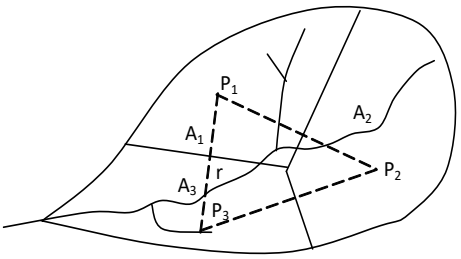


**Figure 1. The example of Thiessen Polygon**
Source: (Triatmodjo, 2009)

**The analysis of sedimentation**

Subsequently, the rainfall analysis results were incorporated into the Universal Soil Loss Equation (USLE) to estimate soil erosion and the volume of eroded watershed material contributing to sedimentation. The development of water-induced soil erosion models began more than seven decades ago, initially using datasets predominantly collected in North America. Among the available approaches, the USLE has become one of the most widely applied empirical models for predicting long-term average soil loss. Its widespread application across various regions and environmental conditions is attributable to its relative simplicity, limited data requirements, and practical ability to represent the principal factors controlling soil erosion (Borrelli et al., 2021; Majhi et al., 2021) .

The rate of soil erosion within a given area is determined by the combined effects of rainfall, soil characteristics, topography, land-management practices, and vegetation cover. In this study, soil loss was estimated using the Universal Soil Loss Equation (USLE), originally developed by Wischmeier and Smith (1960). The general form of the USLE is presented in Equation (7).

$$A = R \times K \times L \times S \times C \times P \quad (7)$$

In Equation (7), $A$ represents the estimated annual soil loss (t ha$^{-1}$ year$^{-1}$); $R$ is the rainfall erosivity factor; $K$ denotes soil erodibility; $L$ represents the slope-length factor; $S$ represents the slope-steepness factor; $C$ is the land-cover and vegetation-management factor; and $P$ denotes the soil-conservation or support-practice factor.

Rainfall erosivity describes the capacity of rainfall to detach soil particles and generate erosion. The rainfall erosivity factor ($R$), initially proposed by Wischmeier and Smith (1958), is commonly derived from the $EI_{30}$ index, which combines the total kinetic energy of a rainfall event with its maximum continuous 30-minute intensity. The annual erosivity value is obtained by summing the $EI_{30}$ values of all erosive rainfall events occurring within rainfall separated from another event by at least six consecutive hours without precipitation (Wischmeier, 1959). This definition was subsequently refined by identifying separate events based on a six-hour period with less than 1.27 mm (0.05 inches) of rainfall (Wischmeier and Smith, 1960). The $EI_{30}$ index is now widely applied in empirical soil-erosion models because it reflects both rainfall energy and peak storm intensity (Oliveira et al., 2013; Nearing et al., 2017). The equations used to calculate rainfall erosivity are presented in Equations (8) and (9).

$$R = \sum(EI30)n \quad (8)$$

$$EI30 = 6{,}199\ (Rb1{,}211)\ (N\text{-}0{,}474)\ (Rm0{,}526) \quad (9)$$

In Equations (8) and (9), $EI_{30}$ represents the rainfall erosivity index, whereas $R$ denotes the annual rainfall erosivity factor. $R_b$ is the average monthly rainfall expressed in centimetres, $N$ is the average number of rainy days per month, and $R_m$ represents the mean maximum daily rainfall for each month, also expressed in centimetres. Soil erodibility refers to the natural vulnerability of soil particles to being detached and transported by rainfall and surface runoff. In the Universal Soil Loss Equation (USLE), this property is expressed by the $K$ factor, which represents the rate of soil loss per unit of rainfall erosivity under standardized plot conditions (Gao et al., 2017). Ideally, the $K$ factor is determined from

long-term measurements conducted on standard erosion plots (Wischmeier and Smith, 1958).

However, obtaining adequate and reliable field observations is often time-consuming because rainfall conditions and soil properties vary spatially and temporally. Consequently, soil erodibility is frequently estimated using readily available information on soil type and physicochemical characteristics (Wang and Zhang, 2021). The $K$-factor values adopted for different soil types in Indonesia are presented in Table 2.

**Table 2. Soil erodibility factors**

| No | Soil type | Soil erodibility gram/joule |
|---|---|---|
| 1 | Latosol soil (oxic subgroup) | 0.02 |
| 2 | Red–yellow Mediterranean soil (Alfisol) | 0.05 |
| 3 | Mediterranean soil (Alfisol) | 0.21 |
| 4 | Red–yellow podzolic soil (Ultisol) | 0.15 |
| 5 | Regosol soil (Inceptisol/Entisol) | 0.11 |
| 6 | Grumusol soil (Vertisol) | 0.24 |

*Source: (Arsyad, 2009)*

Within the USLE framework, topographic effects are represented by the dimensionless $LS$ factor, which combines slope length ($L$) and slope steepness ($S$). This factor reflects the influence of hillslope geometry, including slope form and surface curvature, on soil-erosion processes. Compared with the other USLE components, estimating the $LS$ factor is relatively complex, particularly when applied to heterogeneous natural landscapes (Sabzevari and Talebi, 2019).

Slope characteristics strongly affect erosion because they control the velocity, volume, and erosive energy of surface runoff. Increasing slope steepness generally accelerates runoff and reduces the time available for water to infiltrate the soil, thereby increasing the potential for soil detachment and transport (Kruk et al., 2020). Slope length also influences erosion by determining the distance over which runoff accumulates. Longer slopes typically generate a greater runoff volume and erosive energy, increasing the capacity of overland flow to detach and transport soil particles. The $LS$-factor values adopted in this study based on slope classes are presented in Table 3.

The vegetation-cover factor ($C$) represents the ratio of soil loss from land under a particular vegetation or cropping condition to that from a standard bare-soil control plot. Its value reflects the effectiveness of vegetation in protecting the soil surface, intercepting rainfall, and reducing runoff and erosion. The support-practice factor ($P$) expresses the ratio of soil loss under a specific conservation or land-management practice to that occurring without such measures. In subsequent calculations, the $C$and $P$factors are multiplied to obtain the combined $CP$factor. The $C$- and $P$-factor values adopted in this study are presented in Tables 4 and 5, respectively.

**Table 3. The assessment of slope class**

| Slope class | Slope steepnes (%) | LS values |
|---|---|---|
| A | 0-2 | 0.25 |
| B | 2-5 | 1.2 |
| C | 15-40 | 4.25 |
| D | >40 | 9.5 |

*Source: (Sutapa, 2010)*

**Table 4. The C factor (crop management)**

| No. | Type of land use | C Values |
|---|---|---|
| 1. | Bare or sparsely vegetated land | 1.0 |
| 2. | Paddy field | 0.01 |
| 3. | Unclassified rainfed cropland | 0.7 |
| 4. | Cassava cultivation | 0.8 |
| 5. | Corn | 0.7 |
| 6. | Soybean | 0.399 |
| 7. | Potato | 0.4 |
| 8. | Peanut | 0.2 |
| 9. | Rice | 0.561 |
| 10. | Sugarcane | 0.2 |
| 11. | Banana | 0.6 |
| 12. | Vetiver grass cultivation | 0.4 |
| 13. | First-year Bede grass cultivation | 0.287 |
| 14. | Second-year Bede grass cultivation | 0.002 |
| 15. | Coffee plantation with sparse ground cover | 0.2 |
| 16. | Taro cultivation | 0.85 |
| 17. | Mixed-crop garden or orchard | |
| | – Dense vegetation cover | 0.1 |
| | – Moderate vegetation cover | 0.2 |
| | – Sparse vegetation cover | 0.5 |
| 18. | Shifting cultivation system | 0.4 |
| 19. | Natural forest cover | |
| | – With a thick forest-floor litter layer | 0.001 |
| | – With a thin forest-floor litter layer | 0.005 |
| 20. | Managed production forest | |
| | – Under clear-cut harvesting | 0.5 |
| | – Under selective logging | 0.2 |

*Source: (Arsyad, 2009)*

**Table 5. The P factor values for various soil conservation measures**

| Specific soil conservation measures | P values |
|---|---|
| Bench-terracing system | |
| – Properly constructed and maintained | 0.04 |
| – Moderately constructed and maintained | 0.15 |
| – Poorly constructed or maintained | 0.35 |
| Traditional terrace system | 0.04 |
| Contour strip planting with Bahia grass | 0.4 |
| Contour-aligned tillage and planting | |
| – On slopes of 0%–8% | 0.50 |
| – On slopes of 9%–20% | 0.75 |
| – On slopes exceeding 20% | 0.90 |
| No soil-conservation practices applied | 1 |

*Source: (Arsyad, 2009)*

## Results and Discussion

### Check dams in Unda River

Various structural, vegetative, and management measures have been implemented to mitigate erosion and sediment-related risks within watersheds. Among the structural measures, check dams are widely applied to regulate runoff and sediment transport. These structures are constructed across river channels to reduce flow velocity, limit channel and riverbed erosion, and retain sediment transported from upstream areas. Consequently, check dams can contribute to channel stability and reduce sediment delivery to downstream reaches of the Unda River. (Banihabib and Forghani, 2017)

A total of nine sediment-control structures are located along the Tukad Unda. From upstream to downstream, these structures are designated as UD-CKD1, UD-CKD2, UD-CKD3, UD-CKD4, UD-KOD1, UD-KOD2, UD-CKD5, UD-CKD6, and UD-DPel1, as illustrated in Figure 2. Their sequential distribution forms a sediment-control system intended to regulate sediment transport and reduce sediment delivery to the lower river reaches.

**Figure 2. Check dams in Unda River**

A standardised nomenclature was adopted to identify the river, structure type, and relative location of each structure. The prefix “UD” refers to Tukad Unda, while the subsequent letters indicate the type of sediment-control structure. For example, UD-CKD1 denotes Check Dam 1 on Tukad Unda, where the number identifies its sequence along the river, beginning with the most upstream structure. Other abbreviations, including KOD and DPel, represent different types of hydraulic or sediment-control structures within the system. The locations and longitudinal arrangement of these structures are presented schematically in Figure 2. Based on the field survey, the check dams along the Tukad Unda were found to be largely filled with accumulated sediment, indicating that their available storage capacities had been substantially reduced.

Consequently, these structures can no longer function effectively in retaining sediment and regulating its downstream transport. During high-flow or flood events, previously deposited material may be remobilised and transported downstream, thereby increasing the sediment load and accelerating sedimentation in the lower river reaches. This condition may reduce the river’s conveyance capacity, raise the riverbed elevation, and increase the risk of overbank flooding. Therefore, periodic sediment removal and routine monitoring are required to restore and maintain the hydraulic and sediment-retention functions of the check dams. Examples of sediment accumulation within the check dams are presented in Figure 3.

**Figure 3. The check dam sedimentation**

### Analysis of sedimentation rate

The USLE method is applied to analyse the sedimentation rate in this study. This approach is consistent with previous research demonstrating the practical value of USLE models for assessing soil erosion, while recognizing that their reliability depends on appropriate parameterization, accurate terrain representation, field validation, and consideration of sediment delivery (Alewell et al., 2019; Borrelli et al., 2021; Kruk et al., 2020; Majhi et al., 2021; Sabzevari & Talebi, 2019). Its assessment of check-dam storage capacity also builds on evidence that available storage influences sediment retention, although filled structures may continue to reduce flow velocity and erosive power (Banihabib & Forghani, 2017; Feng et al., 2021). Furthermore, the study complements research on

the Unda and Badung rivers that combined erosion estimation with hydraulic modelling to quantify sediment deposition and identify dredging and structural maintenance requirements (Hidayati et al., 2021; Yekti et al., 2024). It also aligns with basin-scale assessments that identify erosion hotspots to support targeted sediment-management interventions (Kardhana et al., 2024).

The first step in estimating the sedimentation rate was to calculate rainfall erosivity, which reflects the potential of rainfall to initiate soil erosion through raindrop impact and subsequent surface runoff. The analysis used 10 years of rainfall records from the Sidemen, Duda, and Klungkung rainfall stations. Table 6 shows the monthly rainfall erosivity values (EI30). It exhibit substantial seasonal variation, ranging from 27.83 in July to 393.95 in February. The highest erosivity occurred in February, followed by January (308.60), November (234.46), October (229.25), and December (225.15). These elevated values indicate that rainfall during the wet season has greater potential to detach soil particles and generate erosion.

**Table 6. The rain erosivity**

| Erosivity Values (EI30) | | | |
|---|---|---|---|
| **Month** | **Values** | **Month** | **Values** |
| 1 | 308.60 | 7 | 27.83 |
| 2 | 393.95 | 8 | 59.07 |
| 3 | 110.27 | 9 | 69.23 |
| 4 | 130.93 | 10 | 229.25 |
| 5 | 71.63 | 11 | 234.46 |
| 6 | 74.14 | 12 | 225.15 |
| Summary | 1934.50 | | |

In contrast, relatively low erosivity was recorded between May and September, with the minimum value occurring in July. This pattern reflects the lower rainfall amounts and intensities typically observed during the dry season. The total annual rainfall erosivity value was approximately 1,934.50. Overall, the results indicate that the risk of rainfall-induced soil erosion is highest during the wet-season months, particularly from October to February. Therefore, erosion-control measures should be maintained before and throughout this critical period to minimise soil loss and sediment delivery to the Tukad Unda.

Subsequently, the spatial distribution of soil types within the Tukad Unda watershed was identified from the soil map presented in Figure 4. The mapped soil units were then matched with the corresponding erodibility values listed in Table 2. The watershed is predominantly characterised by regosol and latosol soils, which differ in their physical properties and resistance to erosion. Regosols are generally young and weakly developed, making them relatively susceptible to erosion, whereas latosols are more highly weathered and generally have better-developed soil structures. Based on the combination of these soil types and their corresponding reference values, the representative soil erodibility factor for the Tukad Unda watershed was determined to be 0.355. This value was subsequently applied as the K factor in the USLE analysis to estimate soil loss across the watershed.

**Figure. 4 Soil type map of Tukad Unda Watershed**

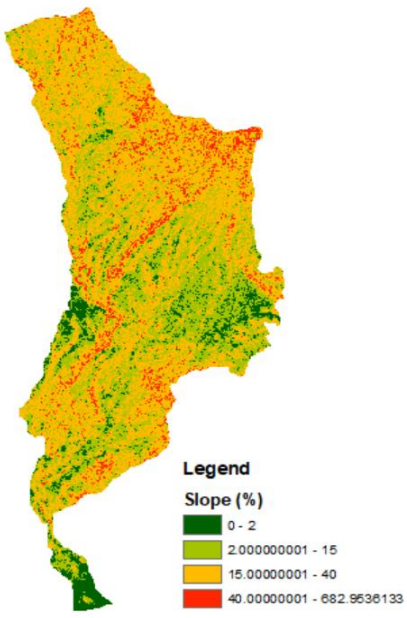


**Figure. 5 Slope steepnes of Tukad Unda Watershed**

Next, the slope length and steepness factor (LS) was based on the erodibility values from Table 3. Based on Figure 5, the areas with slopes of 0–2% and 2–15% each cover of about 20% of the watershed and

contribute weighted LS values of 0.050 and 0.240, respectively. The 15–40% slope class occupies the largest proportion of the watershed of about 40% and contributes 1.700. Although slopes greater than 40% account for only 20% of the watershed, they produce the highest weighted contribution of 2.400 because of their high LS value.

The total weighted LS factor was calculated as 4.39. Approximately 93% of this value is contributed by areas with slopes exceeding 15%, indicating that steep terrain is the dominant topographic control on erosion within the watershed. These areas are therefore expected to generate greater runoff velocity and soil loss and should be prioritised for erosion-control and watershed conservation measures.

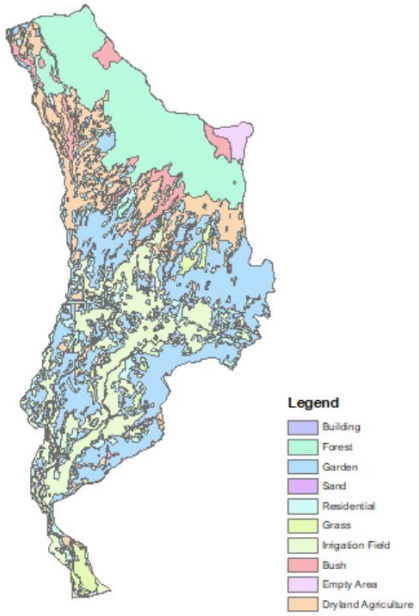


**Figure. 6 Land use of Tukad Unda Watershed**

The land use map in Figure 6 was used to determine the cover-management factor (C) and support-practice factor (P) in the Universal Soil Loss Equation (USLE). Each land use category, such as forest, agricultural land, plantations, grassland, bare land, and settlements, was assigned an appropriate C and P value based on its vegetation cover and land-management practices. The soil conservation factor (P), on the other hand, represents the ratio of soil loss from land with vegetation to that from bare land. The values for both C and P were derived from Tables 4 and 5. Hence, the CP value of 0.1 may reasonably represent the general or dominant watershed condition because a considerable proportion of the mapped area is covered by forest, gardens, shrubs, grassland, irrigated fields, and dryland agriculture. Vegetation can intercept rainfall, reduce raindrop impact, increase surface roughness, and slow overland flow. Agricultural and garden areas may also provide protection through crop cover and land-management measures, such as terracing, contour cultivation, bunding, or other local conservation practices.

Subsquently, nine sediment samples were collected from representative locations along the Tukad Unda, covering the upstream, middle, and downstream reaches. This spatial distribution was selected to account for possible variations in sediment characteristics resulting from differences in sediment sources, transport processes, and depositional conditions. The samples were analysed at the Laboratory of Soil Mechanics, Engineering Faculty at Universoty of Udayana, to determine their specific gravity. The laboratory results produced an average sediment specific gravity of 2.817, indicating that the sediment particles were approximately 2.817 times denser than water.

The measured specific gravity was used to support the conversion of the estimated sediment mass into an equivalent sediment volume. Based on the rainfall erosivity (R), soil erodibility (K), topographic (LS), land-cover (C), and conservation-practice (P) factors incorporated into the USLE, the potential annual sediment volume within the Tukad Unda watershed was estimated to be approximately 118,115.697 m³/year. This estimate represents the potential volume of eroded material generated within the watershed under the assumed sediment-density and delivery conditions.

**The sediment balance**

The sediment balance was evaluated for one, five, and ten-year periods. The analysis assumed that all nine check dams were initially dredged and restored to their full sediment-storage capacities. The results of the sediment balance calculations are presented in Table 7. Table 7 presents the projected sediment balance for the nine sediment-control structures along the Tukad Unda over 1, 5, and 10 year periods. The analysis assumes that all structures are initially empty and that sediment exceeding the storage capacity of an upstream structure is transferred to the next structure downstream. An annual sediment inflow of approximately 118,115.70 m³ was applied in the calculation.

During the first year, the incoming sediment volume remained below the 249,554.37 m³ storage capacity of UD-CKD1. Consequently, all incoming sediment was retained within the most upstream check dam, resulting in no sediment outflow to UD-CKD2 or the other downstream structures. This finding indicates that UD-CKD1 can effectively retain the short-term sediment supply when its storage capacity is fully available.

**Table 7. The sediment balance of Unda River**

| Year | Code | Check dam volume ($m^3$) | The difference between incoming sediment and storage ($m^3$) | Output sediment volume ($m^3$) |
|---|---|---|---|---|
| 1 | UD-CKD1 | 249,554.37 | 0.00 | 0.00 |
| | UD-CKD2 | 378,787.88 | 0.00 | 0.00 |
| | UD-CKD3 | 719,696.97 | 0.00 | 0.00 |
| | UD-CKD4 | 75,757.58 | 0.00 | 0.00 |
| | UD-KOD1 | 56,818.18 | 0.00 | 0.00 |
| | UD-KOD2 | 87,121.21 | 0.00 | 0.00 |
| | UD-CKD5 | 204,545.45 | 0.00 | 0.00 |
| | UD-CKD6 | 227,272.73 | 0.00 | 0.00 |
| | UD-DPel1 | 54,545.45 | 0.00 | 0.00 |
| 5 | UD-CKD1 | 249,554.37 | 341,024.12 | 341,024.12 |
| | UD-CKD2 | 378,787.88 | 0.00 | 0.00 |
| | UD-CKD3 | 719,696.97 | 0.00 | 0.00 |
| | UD-CKD4 | 75,757.58 | 0.00 | 0.00 |
| | UD-KOD1 | 56,818.18 | 0.00 | 0.00 |
| | UD-KOD2 | 87,121.21 | 0.00 | 0.00 |
| | UD-CKD5 | 204,545.45 | 0.00 | 0.00 |
| | UD-CKD6 | 227,272.73 | 0.00 | 0.00 |
| | UD-DPel1 | 54,545.45 | 0.00 | 0.00 |
| 10 | UD-CKD1 | 249,554.37 | 931,602.60 | 931,602.60 |
| | UD-CKD2 | 378,787.88 | 552,814.72 | 552,814.72 |
| | UD-CKD3 | 719,696.97 | 0.00 | 0.00 |
| | UD-CKD4 | 75,757.58 | 0.00 | 0.00 |
| | UD-KOD1 | 56,818.18 | 0.00 | 0.00 |
| | UD-KOD2 | 87,121.21 | 0.00 | 0.00 |
| | UD-CKD5 | 204,545.45 | 0.00 | 0.00 |
| | UD-CKD6 | 227,272.73 | 0.00 | 0.00 |
| | UD-DPel1 | 54,545.45 | 0.00 | 0.00 |

**Table 8. The sediment volumes excavated**

| Code | Volume of check dam ($m^3$) | Excavated sediment ($m^3$) | | |
|---|---|---|---|---|
| | | 1 Yearly | 5 Yearly | 10 Yearly |
| UD-CKD1 | 249,554.37 | 118,115.70 | 249,554.37 | 249,554.37 |
| UD-CKD2 | 378,787.88 | 0.00 | 341,024.12 | 378,787.88 |
| UD-CKD3 | 719,696.97 | 0.00 | 0.00 | 552,814.72 |
| UD-CKD4 | 75,757.58 | 0.00 | 0.00 | 0.00 |
| UD-KOD1 | 56,818.18 | 0.00 | 0.00 | 0.00 |
| UD-KOD2 | 87,121.21 | 0.00 | 0.00 | 0.00 |
| UD-CKD5 | 204,545.45 | 0.00 | 0.00 | 0.00 |
| UD-CKD6 | 227,272.73 | 0.00 | 0.00 | 0.00 |
| UD-DPel1 | 54,545.45 | 0.00 | 0.00 | 0.00 |

After five years, the cumulative sediment inflow was approximately 590,578.49 $m^3$. This volume exceeded the capacity of UD-CKD1 by 341,024.12 $m^3$. Therefore, UD-CKD1 was projected to become completely filled, while the excess sediment was transferred downstream to UD-CKD2. Because the overflow volume remained below the 378,787.88 $m^3$ capacity of UD-CKD2, the sediment was fully retained by this structure, and no sediment was conveyed to UD-CKD3 or farther downstream. At this stage, however, UD-CKD2 had used approximately 90% of its storage capacity, leaving only about 37,763.76 $m^3$ of available storage.

Over the 10-year simulation period, the cumulative sediment inflow reached approximately 1,181,156.97 $m^3$. After the storage capacity of UD-CKD1 was exhausted, approximately 931,602.60 $m^3$ was transferred to UD-CKD2. This volume exceeded the capacity of UD-CKD2 by 552,814.72 $m^3$, which was subsequently conveyed to UD-CKD3. As the storage capacity of UD-CKD3 is 719,696.97 $m^3$, it was sufficient to retain the transferred sediment completely. Accordingly, no sediment outflow was projected from UD-CKD3 to the remaining downstream structures during the analysed period.

The results demonstrate the sequential function of the check-dam system, in which upstream structures retain sediment until their capacities are exhausted, after which the excess sediment is transferred to

downstream structures. UD-CKD1 is expected to reach its storage limit first, followed by UD-CKD2, whereas UD-CKD3 provides sufficient capacity to prevent sediment from reaching the lower river reaches within the 10-year period. Nevertheless, the progressive loss of storage capacity indicates an increasing long-term risk of downstream sediment transport. Periodic monitoring and dredging, particularly at UD-CKD1 and UD-CKD2, are therefore necessary to maintain the effectiveness of the sediment-control system and reduce sedimentation risks downstream.

**The structural mitigation of sedimentation**

Based on the analytical results and field surveys conducted along the Unda River, all check dams from the upstream to downstream reaches should be dredged to restore their sediment-retention capacity and overall functionality. Field observations indicated that the structures were largely filled with deposited material and could no longer trap sediment effectively. The required dredging volumes were therefore estimated by assuming that the sediment-storage capacity of each check dam had been fully occupied. Table 8 presents the estimated sediment volumes requiring excavation under annual, five-year, and ten-year maintenance intervals. The calculations are based on an annual sediment inflow of approximately 118,115.70 m³ and the available storage capacity of each sediment-control structure.

The results illustrate how the selected excavation interval influences the spatial distribution of sediment accumulation along the Tukad Unda. Under an annual excavation programme, approximately 118,115.70 m³ of sediment would be removed from UD-CKD1 each year. Since this volume is lower than its storage capacity of 249,554.37 m³, UD-CKD1 can retain the entire annual sediment inflow, preventing sediment from reaching the downstream structures. This strategy therefore maintains the effective storage capacity of the upstream check dam and minimises downstream sediment transport.

For a five year excavation interval, the cumulative sediment volume is approximately 590,578.49 m³. UD-CKD1 would reach its maximum capacity, requiring the excavation of 249,554.37 m³. The remaining 341,024.12 m³ would be deposited in UD-CKD2 and would also require removal. No excavation would be required at UD-CKD3 or the structures farther downstream because UD-CKD2 would retain all sediment overflowing from UD-CKD1 during this period.

Under the ten year scenario, the cumulative sediment volume would increase to approximately 1,181,156.97 m³. Both UD-CKD1 and UD-CKD2 would reach their respective storage capacities, requiring excavation volumes of 249,554.37 and 378,787.88 m³. The excess sediment would subsequently accumulate in UD-CKD3, where an additional 552,814.72 m³ would need to be excavated. No sediment accumulation requiring excavation is projected at UD-CKD4, UD-KOD1, UD-KOD2, UD-CKD5, UD-CKD6, or UD-DPel1 within the ten-year period.

These findings demonstrate that longer maintenance intervals allow sediment to progressively move from upstream to downstream structures. Although the total excavated volume corresponds to the cumulative sediment generated during each period, delayed excavation increases the number of structures involved and may increase the complexity and cost of maintenance operations. Annual excavation at UD-CKD1 would provide the most effective means of preserving upstream storage capacity and preventing downstream sediment transfer. If annual excavation is operationally or financially impractical, a five-year programme focusing on UD-CKD1 and UD-CKD2 could be adopted as an alternative. However, excavation should be supported by periodic bathymetric or topographic surveys to ensure that maintenance is based on the actual rate of sediment accumulation.

Dredging and sediment-removal activities at the check-dam sites may be implemented collaboratively by relevant government institutions, including BWS Bali–Penida, the Bali Provincial Public Works and Housing Agency (PUPR), and the PUPR agencies of Karangasem and Klungkung regencies. To reduce operational costs, the Bali Provincial Government could establish a regional regulatory framework that permits community participation in sediment extraction along the Unda River under village-level coordination. These activities may be managed through village-owned enterprises (BUMDes) or cooperatives, with technical supervision and monitoring provided by BWS Bali–Penida as the authority responsible for managing the Unda River Basin.

All sediment-extraction activities must obtain the required permits and comply with applicable mining and environmental regulations administered by the Energy and Mineral Resources Agency (ESDM). Relevant regulatory references include Law No. 3 of 2020, particularly Article 68A; Presidential Regulation No. 55 of 2022; Minister of Energy and Mineral Resources Regulation No. 5 of 2021; and Bali Governor's Decree No. 930/03-

M/HK/2022 concerning technical guidelines for non-metallic mineral and rock-mining permits in Bali Province. Operational activities should also follow the principles of good mining practice stipulated in Article 3(3) of Minister of Energy and Mineral Resources Regulation No. 26 of 2018. These provisions should guide licensing, extraction methods, environmental protection, occupational safety, monitoring, and post-mining site management.

**The non-structural mitigation of sedimentation**

Non-structural mitigation in the Unda River Basin should focus on strengthening the regulatory framework, improving disaster-risk education, and increasing public awareness. Communities living in hazard-prone areas must understand the risks associated with erosion, sedimentation, flooding, and related watershed degradation, as well as their roles in reducing these risks. Community-based mitigation is particularly important because it encourages local ownership, strengthens long-term commitment, and positions residents as both beneficiaries and active participants in disaster-risk reduction.

According to Bali Governor Regulation No. 5 of 2013 concerning the Disaster Management Plan, disaster management comprises a series of measures that include risk-sensitive development policies, disaster prevention, emergency response, rehabilitation, and reconstruction. The regulation also emphasizes the need for cooperation among government institutions, communities, and the private sector to protect the public from disaster threats, risks, and impacts. Accordingly, sediment- and flood-risk management in the Unda River Basin should be incorporated into broader regional development and disaster-management policies.

Nevertheless, regulations and public information alone may be insufficient to ensure the long-term effectiveness of non-structural mitigation. Disaster awareness should be internalized within community behaviour and reinforced through established social norms. The development of disaster-resilient communities therefore requires continuous collaboration between government institutions and local stakeholders in planning, implementing, monitoring, and evaluating mitigation programmes. Such collaboration can help ensure that mitigation practices are consistent with the social values, customary institutions, and local governance systems of communities along the Unda River.
Social and cultural capital can provide a strong foundation for community-based mitigation. In this context, cultural capital includes local knowledge, customary practices, and collective values maintained by villages situated along the river. Existing social and cultural resources can be strengthened through several measures such as, the implementation of non-structural mitigation in the Unda River Basin should actively engage traditional leaders, community representatives, and other influential local figures as strategic partners in communicating and implementing mitigation policies. Their involvement can improve public acceptance and ensure that mitigation measures are consistent with local values and community practices. Relevant stakeholders should also participate throughout the policy process, including the formulation, implementation, monitoring, and evaluation of disaster-risk-reduction programmes. This participatory approach should be supported by transparent and continuous communication among government agencies, watershed authorities, private-sector actors, and local communities. Recognition and appropriate incentives may be provided to individuals, community groups, and organizations that contribute to environmental protection and the long-term sustainability of the watershed. Formal cooperation should also be established among government institutions and local administrative units, particularly villages and *banjar*, to clarify responsibilities and strengthen coordination. Furthermore, community-development programmes should integrate disaster mitigation with religious, educational, sociocultural, environmental, and sustainable livelihood activities. Broad participation by local communities, academic institutions, businesses, and civil-society organizations should ultimately be encouraged to strengthen collective capacity and reduce disaster risks in vulnerable areas along the Unda River.

Through these measures, non-structural mitigation can complement dredging and other engineering interventions by strengthening institutional coordination, community preparedness, and the long-term sustainability of sediment management in the Unda River Basin.

## Conclusion

This study provides a practical basis for sediment management in the Unda River Basin by linking estimated sediment accumulation with check-dam storage capacity and evaluating annual excavation scenarios to support maintenance planning. The findings emphasize the need to combine dredging and controlled sediment mining with government coordination, community participation, and disaster-risk awareness. This integrated approach can guide sediment removal priorities, support the maintenance of sediment-control structures, and strengthen coordinated mitigation across the basin.

The field survey and sediment-balance analysis indicate that most check dams along the Unda River have been substantially filled with sediment, reducing their capacity to retain sediment and limit its downstream transport. Based on the USLE analysis and the assumed sediment-delivery and density conditions, the potential annual volume of erosion-derived sediment was estimated at approximately 118,115.70 m³. If the check dams are initially restored to their full capacities, annual removal of this volume from UD-CKD1 would prevent sediment from reaching downstream structures. Under a five-year maintenance interval, approximately 249,554.37 m³ and 341,024.12 m³ would need to be removed from UD-CKD1 and UD-CKD2, respectively. For a ten-year interval, dredging volumes of approximately 249,554.37 m³, 378,787.88 m³, and 552,814.72 m³ would be required at UD-CKD1, UD-CKD2, and UD-CKD3, respectively.

Annual dredging of UD-CKD1 is therefore recommended as the most effective strategy for maintaining upstream storage capacity and limiting downstream sediment transfer. Where annual dredging is financially or operationally impractical, a five-year maintenance programme focusing on UD-CKD1 and UD-CKD2 may be adopted, supported by periodic topographic or bathymetric surveys. Sediment removal may be undertaken by government agencies or through regulated community participation involving village-owned enterprises or cooperatives. These structural measures should be complemented by non-structural interventions, including regulatory enforcement, public education, stakeholder coordination, community-based monitoring, and the integration of local institutions and customary practices. Together, these measures provide a practical framework for sustainable sediment management and disaster-risk reduction in the Unda River Basin.

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